Status of VLBI Observations at 1 mm Wavelength and Future Prospects

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Introduction

One of the main motivations for high angular resolution imaging at wavelengths shorter than 3 mm comes from the need to image the innermost structures of AGN and their jets on scales as close as possible to the Schwarzschild radii of the central supermassive objects. At a wavelength of 1.3 mm (~ 230 GHz), VLBI observations with transcontinental baselines yield angular resolutions as small as 25 micro-arcseconds (μas). This corresponds to a spatial resolution of 52 light days for 3C 273 (z=0.158, $H_0 = 100$ km s^{-1} Mpc^{-1}, $q_0 = 0.5$). Since most compact radio sources are self-absorbed at longer wavelengths (or scatter broadened in the case of Sgr A*), VLBI imaging at 1 or 2 mm wavelength should offer a clear view to the nucleus, less affected by opacity effects.

While VLBI imaging at 3 mm with the CMVA (Coordinated Millimeter VLBI Array) is now fairly standard (maps with dynamic range of a few hundred are obtained from experiments involving up to 12 stations), VLBI observations at shorter wavelengths are still limited to single baseline detection experiments. With the foreseeable detection of 1 mm fringes on short baselines also on both sides of the Atlantic, as a next step, the combination of the European and American sub-arrays can be envisaged. With a global array operating near λ =1 mm ($\nu = 230$ GHz) and utilizing phased interferometers (at Plateau de Bure, Ovro, and Hat Creek) as sensitive elements, micro-arcsecond VLBI imaging should become possible within the next few years.

Summary of Previous Experiments

The first VLBI tests at the highest frequencies yet attempted ($1.3 - 1.4$ mm) were carried out in 1990, 1994, and 1995. These tests were mainly technically driven and were performed to demonstrate the feasibility of 1 mm VLBI. A first experiment performed in 1990 yielded weak (SNR= 5) fringes on 3C 273 on the 845 km baseline Ovro-Kitt Peak (Padin et al., 1990). After this, two VLBI experiments were performed in 1994 and 1995, using the 1150 km baseline between the 30 m MRT at Pico Veleta (Spain) and a single 15 m antenna of the IRAM interferometer on Plateau de Bure (France). On this baseline fringes with a fringe spacing of $0.2 - 0.4$ mas are obtained. With system equivalent flux densities of SEFD= 2800 Jy for Pico Veleta and SEFD= 11500 Jy for Plateau de Bure, respectively, the single baseline detection threshold (7σ) is 1.3 Jy for incoherent averaging and 0.5 Jy, if coherent averaging can be applied (see below).

The first of these two experiments was made in December 1994. This experiment was solely technically driven and was performed to demonstrate the feasibility of 1 mm VLBI using the two IRAM instruments. After observations at 86 GHz which were used to determine the station clock offsets, the sources 3C 273 ($S_{215\mathrm{GHz}} = 13.5$ Jy), 3C 279 ($S_{215\mathrm{GHz}} = 10.5$ Jy), and 2145+067 ($S_{215\mathrm{GHz}} = 5.6$ Jy) were observed and detected with signal-to-noise ratios in the range of SNR=$7-10$ (Greve et al., 1995). 1823+568 which had a flux of only 1.5 Jy was not seen.

A second observation took place in March 1995, using the same antennas and observational setup (MK III mode A, 112 MHz bandwidth). In this experiment which was of longer duration, a sample of 8 bright AGN and the Galactic Center source Sgr A* were observed (Krichbaum et al. 1997 & 1998). From this small sample, only the faintest source, 4C 39.25, which had a flux of $S_{215\mathrm{GHz}} = 3.5$ Jy, was not detected. For the remaining 8 objects (3C 273, 3C 279, 1334-127, 3C 345, NRAO 530, Sgr A*, 1749+096, 1921-293) clear fringes were found with signal-to-noise ratios in the range of SNR=$6 - 35$.

In 1994 and 1995 3C 273 and 3C 279 were observed at similar interferometric hour angles (IHA). This facilitates a comparison of their correlated flux densities between the two epochs. Whereas for 3C 279 the total flux density and the visibility amplitudes between both experiments were similar ($S_{corr} = 2.4 - 2.8$ Jy at IHA= 4), the correlated flux in 3C 273 (at IHA= $2 - 3$) increased by a factor of two from $S_{corr} = 0.5$ Jy in December 1994, to $S_{corr} = 1.0$ Jy in March 1995. On the other hand the total flux of 3C 273 decreased from 13.5 Jy to 9.2 Jy. This and the superluminal motion seen in 3C 273 at longer wavelengths, can be regarded as evidence for structural variations in the jet of 3C 273 also at 215 GHz.

The highest correlated flux of about 4 Jy was seen in 3C 279. This corresponds to a visibility (or compactness) of about 40 %. For the other sources the visibilities were lower, ranging between 10–30 %. At present it is unclear, if these lower visibilities are due to residual calibration uncertainties, or if they indicate angular resolution effects. All of the sources were observed in snapshot mode for only a limited time range. The beating in the visibility amplitude, which is caused by the mas-to sub-mas structure of the individual source and which often is quite pronounced in the 3 mm data, easily could cause an underestimate of the correlated flux density and therefore would represent only a lower limit to the compactness.

Recent 3 mm maps of 3C 273 (T. Krichbaum et al., this conference) show a one-sided core jet structure with a compact core of $\sim 80\,\mu$as size and a brightness temperature $T_B = 2.1 \cdot 10^{11}$ K close to the theoretically expected inverse Compton limit ($T_B \sim 10^{12}$ K). Using this measured brightness temperature, the expected source size at 230 GHz would be $\theta = 10.5\sqrt{S_{Jy}}\,\mu$as. With a total flux density of $S = 10$ Jy, the expected source size would be $33\,\mu$as. This yields a visibility of $V = 0.96$ or $S_{corr} = 9.6$ Jy at $700\,M\lambda$ (Pico – PdBure) and $V = 3.9 \cdot 10^{-2}$ or $S_{corr} = 0.4$ Jy at $6000\,M\lambda$ (transatlantic baselines).

In order to detect compact sources like 3C 273 on the long transatlantic baselines, a detection sensitivity of $\simeq 0.4$ Jy is needed. There might be sources which are more compact, but they will be fainter. For a 1 Jy source with a size of $10\,\mu$as a correlated flux of $0.7 - 0.8$ Jy could be expected, relieving the sensitivity requirements by a factor of two. To reach the necessary sensitivity, future 1 mm VLBI will require participation of antennas with large collecting areas (phased interferometers like Plateau de Bure, OVRO, BIMA, and the future MMA and ALMA), high observing bandwidths ($\Delta\nu \geq 256$ MHz), and the possibility to correct for atmospheric phase fluctuations, which if uncorrected, lead to too short coherence times (see Tahmoush & Rogers, this conference).

A 1 mm-VLBI Experiment in February 1999

Past 1mm-VLBI detections and scientific results are encouraging but have, so far, been limited to single baselines. For AGN studies at 1 mm, imaging arrays are needed that include many more antennas. Observations of compact masers at the highest VLBI frequencies require relatively compact arrays with baselines less than $1G\lambda$. A group of five 1mm equipped mm-wave dishes in the SouthWest United States can potentially deliver a scientifically useful 1mm-VLBI array. This group includes : the Berkeley-Illinois-Maryland Array (Redding, CA), the Owens Valley Radio Observatory (Bishop, CA), the NRAO 12m (Kittpeak, AZ) and the Heinrich Hertz Telescope (Mt. Graham, AZ).

A 1mm-VLBI experiment was carried out with the above array plus the IRAM 30m on Pico Veleta during the winter season in 1999. Good weather is crucial for experiments at high frequencies especially since the smaller antenna sizes typical of this array raise detection thresholds. Recording began at 0600 UT on 17 Feb and ended at 1800UT on Feb 19. All sites recorded in MKIII compatible modes with VLBA sites (Kittpeak, OVRO) using 7 BBCs each 8MHz wide (56MHz BW), and all other sites using a full compliment of 14 BBCs for a total of 112MHz bandwidth. The center observing frequency was 230.5 GHz.

All sites other than the HHT routinely participate in CMVA 3mm-VLBI sessions so special preparations there were required. A MKIII VLBI electronics rack and a tape recorder were shipped to Mt. Graham a month early and set up for testing. A H-maser was borrowed from the Harvard-SAO and shipped along with the VLBI equipment. Standard phase tests carried out at the HHT confirmed that 1mm test tones injected into the receiver feed recorded properly on tape and could be recovered at the Haystack correlator. As a further check, the CO J=2-1 line at 230.5GHz was observed towards the cold core L1512, recorded using the VLBI system and its spectra generated by autocorrelating the tape at Haystack. Geodetic GPS measurements were made to determine the HHT position to within 1 meter. Personnel from the MPIfR created the important software links from the VLBI field system to the HHT pointing computer.

Target sources included the brightest compact AGN and placed emphasis on 3C279 and 3C273B which were both at $\sim$ 10Jy. Historically, they have been at higher flux density levels. The compact source SgrA* was also included as it has a rising spectrum from 3 to 1mm.

Bad weather at OVRO and BIMA made phasing the arrays difficult and we estimate that during times of good mutual visibility of bright sources on the VLBI array, these sites were unphased. Baselines to Pico Veleta, while potentially the most sensitive, were observed at very low elevations for antennas in the US with correspondingly higher Tsys values. The table shows the antenna sensitivities corresponding to the best times of mutual visibility on 3C273B and 3C279.

Site	Diam	Tsys (K)	SEFD (Jy)
HHT	10m	375	22000
Kittpeak	12m	450	24000
Pico Veleta	30m	300	2500
BIMA	9×6m	700	74000*
OVRO	4×8m	1000	59000*

* Unphased

Searching for Fringes

Tapes were shipped to the Haystack Correlator and fringes were searched for to all sites. Searches concentrated on the Kittpeak-HHT baseline which observed 3C279 and 3C273B at optimal elevations and during periods of good weather. Station clocks determined using GPS receivers at each site limited fringe searches in delay to a few micro seconds but delay windows of up to $\pm 28 \mu sec$ were searched. No sources were detected using a combination of coherent and incoherent detection methods.

Sensitivity

An expression for the coherent detection threshold for a single baseline can be written as :

$$D_c = \frac{7\sqrt{\mathrm{SEFD_1\ SEFD_2}}}{L\ \sqrt{2B\tau_c}} \tag{1}$$

where $L \sim 0.5$ is the loss due to 1-bit sampling, B is the bandwidth, and τ_c is the coherent integration time. For the Kittpeak-HHT baseline, the detection level for a coherence time of 10 seconds is 9.6 Jy. This threshold can be lowered by averaging many coherent segments (Rogers, Doeleman & Moran 1995) which is very useful in the high frequency regime where τ_c can easily be less than 10 seconds. This incoherent detection threshold (D_i) can be expressed as $D_i \sim D_c\ N^{-0.25}$ where N is the number of coherent segments averaged. For scans of 6.5 minute length, the incoherent detection threshold is lowered to $D_i = 3.2$Jy. The obvious question of why there were no detections with a

detection threshold well below the source flux densities leads us to consider sources of loss in the VLBI systems.

Test tones traced through the receiver systems at both Kittpeak and HHT revealed no more than a 20% signal loss. This loss alone would cause D_i to increase by a factor of 1.25. A more severe loss of signal can come from decorrelation due to phase noise on the maser reference. The maser coherence loss is $\exp(-\sigma^2/2)$ with $\sigma = 2\pi\nu\sigma_y(\tau)\tau$ where $\sigma_y(\tau)$ is the Allan Standard Variance at the coherence time τ and ν is the observing frequency. Investigation into the performance of the HHT H-maser shows that it may have had an Allan Variance in excess of 8e-14 for a 10 second coherence time causing a 50% loss in signal. By comparison, the Kittpeak H-maser, with a variance of 2.4e-14 has a loss of only 4%. Combining these two sources of loss raises D_i to 6Jy. This leaves even the incoherent detection method with only a marginal chance of detecting the source on this baseline. If we consider other possible factors such as source resolution on the $200M\lambda$ baseline or coherence times less than 10 seconds, then the situation becomes even worse. We conclude that the sum of these losses combined with uncooperative weather to raise detection thresholds on this baseline above flux densities of our brightest targets.

Future Experiments - 2mm

A compromise between the elevated detection thresholds at 230GHz and the need to explore VLBI at higher frequencies may be to attempt 2mm-VLBI. The sensitivity advantages are clear. The atmospheric opacity is much lower and coherence times are longer than at 1mm. System temperatures decrease while source flux densities rise : at 150GHz the flux density of 3C273B is 13Jy (down from its historical level of 18Jy). Effects of phase noise in the maser reference also decrease. Using 2mm SEFDs of 17500Jy and 19500Jy for the HHT and Kittpeak respectively, we find that $D_i(10\text{ sec})$=3.3Jy with all the above losses accounted for. For the spectral line case, if we assume a line width of 0.5km/s, then $D_c(10\text{ sec})$=100Jy. A number of SiO masers in evolved stars exceed this flux density in the 2mm range and may be the best class of fringe finders at the higher frequencies. Plans are underway for a 2mm-VLBI test involving HHT-Kittpeak-Pico Veleta in early 2000.

Acknowledgements

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